Linking land use and climate: the key role of uncertainty and spatial location

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Appendix C

C1 Methods

Table C-1. Default values for socioeconomic scenario variables. Sources: Nakicenovic and Swart [2000], van Vuuren *et al.* [2011], van Vuuren and Carter [2014], and IIASA [2015].

Scenario type	Scenario	Global population 2100 (billion)	GDP total growth to 2100 (%/yr)	Inequality ratio 2100*	CO_2 2100 (ppm CO_2e)+	Technology change	Global trade
SRES	A1 (A1B)	7.0	2.90	1.61	700	Rapid	High
SRES	A2	15.0	2.30	4.18	850	Slow	Constrained
SRES	B1	7.0	2.50	1.81	550	Medium	High
SRES	B2	10.0	2.20	3.02	620	Medium	Constrained
SSP	SSP1	6.9	2.44	1.35	650 (RCP4.5)	Rapid	Moderate
SSP	SSP2	9.0	2.38	1.69	850 (RCP6.0)	Medium	Moderate
SSP	SSP3	12.7	1.64	3.47	1370 (RCP8.5)	Slow	Constrained
SSP	SSP4	9.4	1.91	3.78	850 (RCP6.0)	Medium	Moderate
SPP	SSP5	7.4	3.11	1.26	1370 (RCP8.5)	Rapid	High
Present	Present	6.9	0.00	5.80	390 (Present)	None	Moderate

*Ratio of per capita incomes between OECD and non-OECD countries.
+Used as a proxy to driving climate change within scenario, potentially via climate or yield projections input into land-use or land-cover model. Radiative forcing was not included as it is highly correlated to the CO_2-level in the RCP scenarios.

Table C-3. Multiple regression variables used for variance analysis.

Variable	Data type	Group
Initial condition delta, from 2010 baseline	Numeric	Initial
Model type	Categorical (CGE, PE, Rule-based, Hybrid)	Model
Model extent*	Categorical (Global, Europe)	Model
Number model cells (log)	Numeric	Model
CO_2 concentration 2100	Numeric	Climate scenario
Population in 2100	Numeric	Socioeconomic scenario
GDP growth rate to 2100	Numeric	Socioeconomic scenario
Inequality ratio in 2100	Numeric	Socioeconomic scenario
Technology change	Numeric 0=None, 1=Slow, 2=Medium, 3=Rapid+	Socioeconomic scenario
Global trade	Numeric 1=Constrained, 2=Moderate, 3=High+	Socioeconomic scenario

*Used only in analysis at a European extent.
+Meaningful values would have been preferred, as per inequality, to capture information on the separation between categories. However, appropriate information for these variables was not available for the SRES or SSP scenarios.

Table C-2. Model scenario characterization data.

Model	Scenario ID	Socioeconomic scenario	Climate scenario	Global population 2100 (billion)	GDP growth to 2100 (%/yr)	Inequality ratio 2100	CO_2 2100 (ppm CO_2e)+	Technology change	Global trade
AIM	SSP1	SSP1	Present	6.9	2.40	1.35	390	Rapid	Moderate
AIM	SSP2	SSP2	Present	9.0	2.40	1.69	390	Medium	Moderate
AIM	SSP3	SSP3	Present	12.7	1.60	3.47	390	Slow	Constrained
CAPS	Sim1	SSP3	RCP8.5	12.7	1.60	3.47	1370	Slow	Constrained
CAPS	Sim2	SSP3	RCP8.5	12.7	1.60	3.47	1370	Slow	Constrained
CAPS	Sim3	SSP5	RCP8.5	7.4	3.10	1.26	1370	Rapid	High
CAPS	Sim4	SSP5	RCP8.5	7.4	3.10	1.26	1370	Rapid	High
CAPS	Sim5	B1	RCP4.5	7.0	2.50	1.81	650	Medium	High
CAPS	Sim6	B1	RCP4.5	7.0	2.50	1.81	650	Medium	High
CAPS	Sim7	A2	RCP8.5	15.0	2.30	4.18	1370	Slow	Constrained
CAPS	Sim8	A2	RCP8.5	15.0	2.30	4.18	1370	Slow	Constrained
CLUMondo	FAO4D	SSP2	Present	9.0	2.40	1.69	390	Medium	Moderate
CLUMondo	CARBON	SSP2	Present	9.0	2.40	1.69	390	Medium	Moderate
CLUMondo	PPA	SSP2	Present	9.0	2.40	1.69	390	Medium	Moderate
CRAFTY	A1	A1	A1	7.0	2.90	1.61	700	Rapid	High
CRAFTY	B1	B1	B1	7.0	2.50	1.81	550	Medium	High
CLIMSAVE-IAP	A1-A1	A1	A1*	7.0	2.90	1.61	700	Rapid	High
CLIMSAVE-IAP	A2-A2	A2	A2*	15.0	2.30	4.18	850	Slow	Constrained
CLIMSAVE-IAP	B1-B1	B1	B1*	7.0	2.50	1.81	550	Medium	High
CLIMSAVE-IAP	B2-B2	B2	B2*	10.0	2.20	3.02	620	Medium	Low
CLIMSAVE-IAP	Baseline-A1	Baseline	A1*	6.9	0.00	5.80	700	None	Moderate
CLIMSAVE-IAP	Baseline-A2	Baseline	A2*	6.9	0.00	5.80	850	None	Moderate
CLIMSAVE-IAP	Baseline-B1	Baseline	B1*	6.9	0.00	5.80	550	None	Moderate
CLIMSAVE-IAP	Baseline-B2	Baseline	B2*	6.9	0.00	5.80	620	None	Moderate
DynaCLUE	A1	A1	A1	7.0	2.90	1.61	700	Rapid	High
DynaCLUE	A2	A2	A2	15.0	2.30	4.18	850	Slow	Constrained
DynaCLUE	B1	B1	B1	7.0	2.50	1.81	550	Medium	High
DynaCLUE	B2	B2	B2	10.0	2.20	3.02	620	Medium	Low
EcoChange	BBCN	A2	A2	15.0	2.30	4.18	850	Slow	Constrained
EcoChange	BBSL	A2	A2	15.0	2.30	4.18	850	Slow	Constrained

Table C-2. (continued).

Model	Scenario ID	Socioeconomic scenario	Climate scenario	Global population 2100 (billion)	GDP growth to 2100 (%/yr)	Inequality ratio 2100	CO_2 2100 (ppm CO_2e)+	Technology change	Global trade
EcoChange	BMBU	A2	A2	15.0	2.30	4.18	850	Slow	Constrained
EcoChange	GRAS	A1	A1	7.0	2.90	1.61	700	Rapid	High
EcoChange	GSCT	A1	A1	7.0	2.90	1.61	700	Rapid	High
EcoChange	SEDG	B1	B1	7.0	2.50	1.81	550	Medium	High
FABLE	scenario_1	FableA-A1B	RCP2.6	10.4	2.25	1.61	490	Rapid	High
FABLE	scenario_2	FableB-A1B	RCP8.5	10.4	2.25	1.61	1370	Rapid	High
FABLE	scenario_3	FableA-A1B	RCP2.6	10.4	2.25	1.61	490	Rapid	High
FABLE	scenario_4	FableC-A1B	RCP2.6	10.4	2.00	1.61	490	Rapid	High
FABLE	scenario_5	FableD-A1B	RCP2.6	12.3	2.25	1.61	490	Rapid	High
FABLE	scenario_6	FableA-A1B	RCP2.6	10.4	2.25	1.61	490	Rapid	High
FALAFEL	SSP1	SSP1	Present	6.9	2.40	1.35	390	Rapid	Moderate
FALAFEL	SSP2	SSP2	Present	9.0	2.40	1.69	390	Medium	Moderate
FALAFEL	SSP3	SSP3	Present	12.7	1.60	3.47	390	Slow	Constrained
FALAFEL	SSP4	SSP4	Present	9.4	1.90	3.78	390	Medium	Moderate
FALAFEL	SSP5	SSP5	Present	7.4	3.10	1.26	390	Rapid	High
FARM	SSP1 RCP4.5	SSP1	RCP4.5	6.9	2.40	1.35	650	Rapid	Moderate
FARM	SSP1 present climate	SSP1	Present	6.9	2.40	1.35	390	Rapid	Moderate
FARM	SSP2 RCP6.0	SSP2	RCP6.0	9.0	2.40	1.69	850	Medium	Moderate
FARM	SSP2 present climate	SSP2	Present	9.0	2.40	1.69	390	Medium	Moderate
FARM	SSP3 RCP8.5	SSP3	RCP8.5	12.7	1.60	3.47	1370	Slow	Constrained
FARM	SSP3 present climate	SSP3	Present	12.7	1.60	3.47	390	Slow	Constrained
GCAM	SSP1	SSP1	Present	6.9	2.40	1.35	390	Rapid	Moderate
GCAM	SSP2	SSP2	Present	9.0	2.40	1.69	390	Medium	Moderate
GCAM	SSP3	SSP3	Present	12.7	1.60	3.47	390	Slow	Constrained
GCAM	SSP4	SSP4	Present	9.4	1.90	3.78	390	Medium	Moderate
GCAM	SSP5	SSP5	Present	7.4	3.10	1.26	390	Rapid	High
GLOBIOM	SSP1	SSP1	Present	6.9	2.40	1.35	390	Rapid	Moderate
GLOBIOM	SSP2	SSP2	Present	9.0	2.40	1.69	390	Medium	Moderate
GLOBIOM	SSP3	SSP3	Present	12.7	1.60	3.47	390	Slow	Constrained
IMAGE	SSP2_450_BECCS	SSP2	RCP2.6	9.0	2.40	1.69	490	Medium	Moderate
IMAGE	SSP2_450_REF	SSP2	RCP2.6	9.0	2.40	1.69	490	Medium	Moderate
LUISA	reference	SSP2	RCP6.0	9.0	2.40	1.69	850	Medium	Moderate
LandSHIFT	FUEL_BAU	SSP2	Present	9.0	2.40	1.69	390	Medium	Moderate
LandSHIFT	FUEL_REGULATIONS	SSP2	Present	9.0	2.40	1.69	390	Medium	Moderate
LandSHIFT	HEAT_BAU	SSP2	Present	9.0	2.40	1.69	390	Medium	Moderate
LandSHIFT	HEAT_REGULATIONS	SSP2	Present	9.0	2.40	1.69	390	Medium	Moderate
MAGNET	SSP1	SSP1	RCP4.5	6.9	2.40	1.35	650	Rapid	Moderate

Table C-2. (continued).

Model	Scenario ID	Socioeconomic scenario	Climate scenario	Global population 2100 (billion)	GDP growth to 2100 (%/yr)	Inequality ratio 2100	CO_2 2100 (ppm CO_2e)+	Technology change	Global trade
MAGNET	SSP2	SSP2	RCP6.0	9.0	2.40	1.69	850	Medium	Moderate
MAGNET	SSP3	SSP3	RCP8.5	12.7	1.60	3.47	1370	Slow	Constrained
MAgPIE	BAU	SSP2	Present	9.0	2.40	1.69	390	Medium	Moderate
MAgPIE	BECCS	SSP2	Present	9.0	2.40	1.69	390	Medium	Moderate
PLUM	A1	A1	A1	7.0	2.90	1.61	700	Rapid	High
PLUM	A2	A2	A2	15.0	2.30	4.18	850	Slow	Constrained
PLUM	B1	B1	B1	7.0	2.50	1.81	550	Medium	High
PLUM	B2	B2	B2	10.0	2.20	3.02	620	Medium	Low

+CO_2-level impacting productivity and agroclimatic regions.

*Emissions scenario applied to climate models.

C2 Results

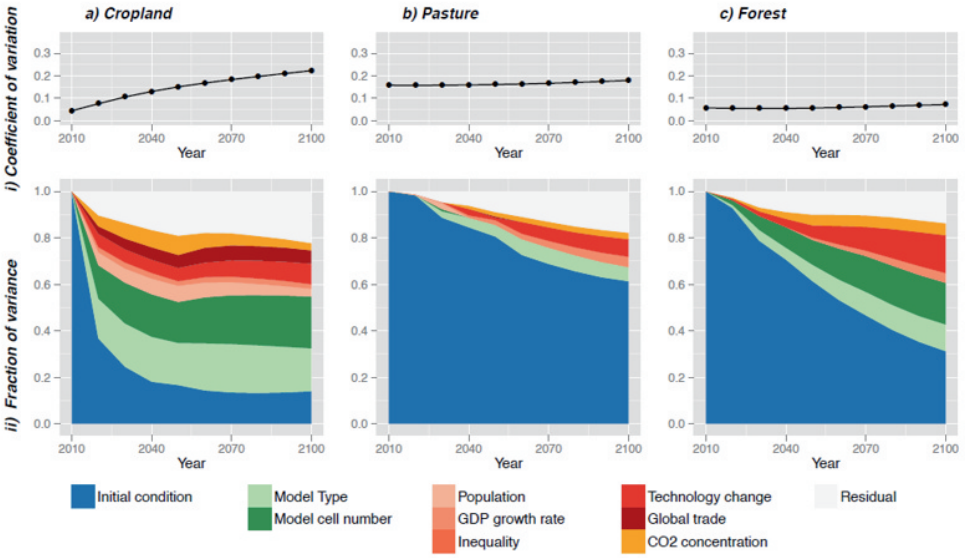

Figure C-1. Total coefficient of variation (i) and relative importance of different variance components (ii) restricted to results that extend to 2100, for global land-cover areas.

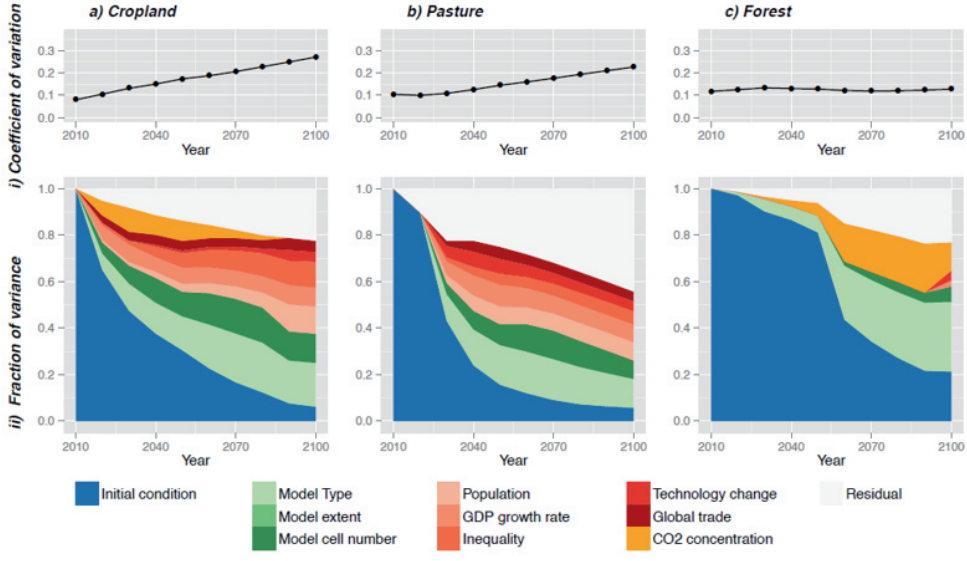

Figure C-2. Total coefficient of variation (i) and relative importance of different variance components (ii) restricted to results that extend to 2100, for European (EU27) land-cover areas.

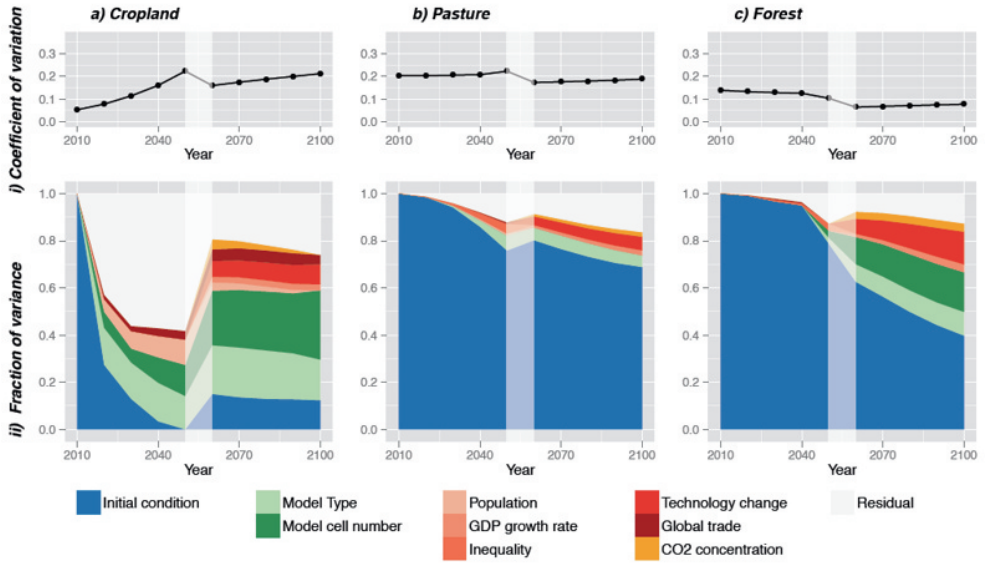

Figure C-3. Total coefficient of variation (i) and relative importance of different variance components (ii) weighted by the reciprocal of the number of scenarios for each model, for global land-cover areas.

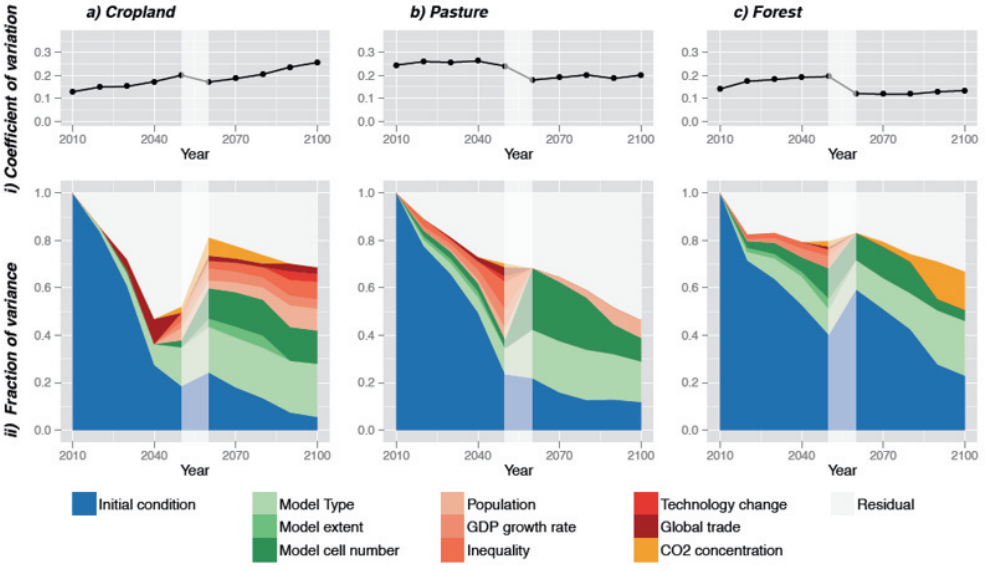

Figure C-4. Total coefficient of variation (i) and relative importance of different variance components (ii) weighted by the reciprocal of the number of scenarios for each model, for European (EU27) land-cover areas.

Figure C-5. Total coefficient of variation (i) and relative importance of different variance components (ii) removing extreme scenario results (i.e., those that exceed 1.96 standard deviations from the model mean in the last year of the model run), for global land-cover areas. 2, 3, or 4 scenarios were identified and removed from AIM, FALAFEL, CLU-Mondo, GCAM, or LandSHIFT, depending on land cover.

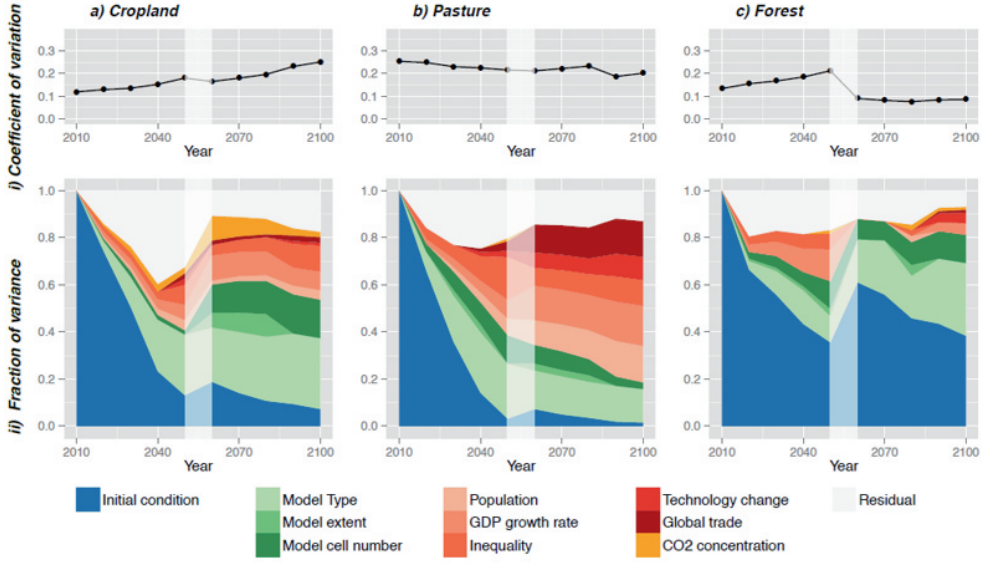

Figure C-6. Total coefficient of variation (i) and relative importance of different variance components (ii) removing extreme scenario results (i.e., those that exceed 1.96 standard deviations from the model mean in the last year of the model run), for European (EU27) land-cover areas. 3 or 4 scenarios were identified and removed from AIM, CLIMSAVE-IAP, CRAFTY or PLUM depending on land cover.

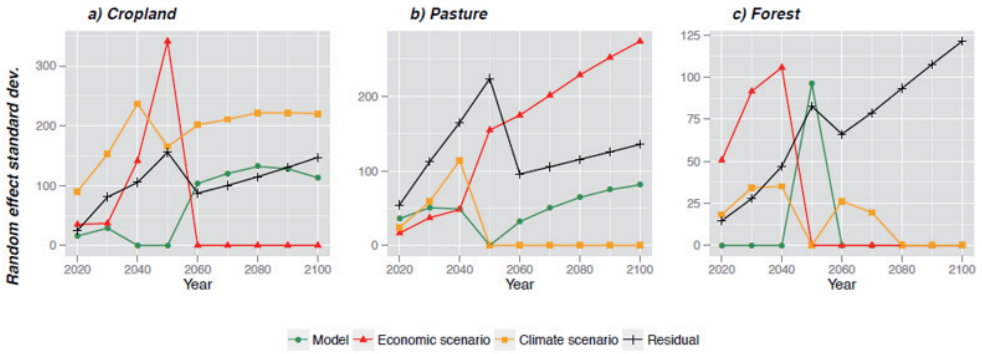

Figure C-7. Random effect standard deviations for global data from a mixed model, with the fixed effects as per Table C-3 and random effects for the model, and socioeconomic and climate scenario.

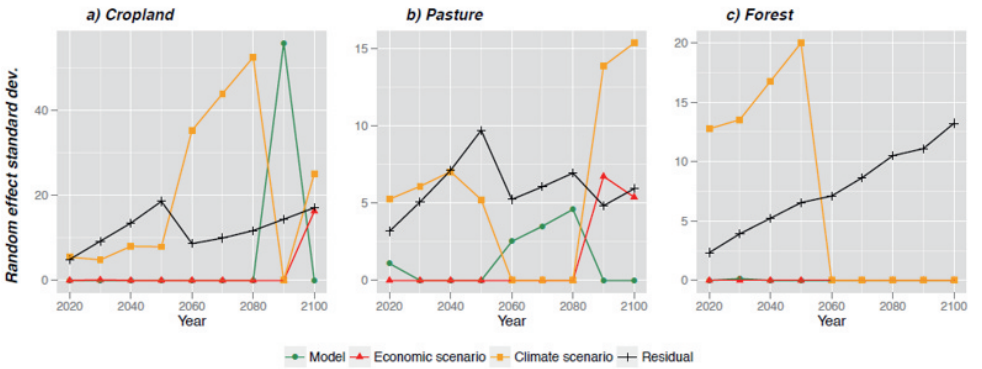

Figure C-8. Random effect standard deviations for European (EU27) data using a mixed model, as Figure C-7.

C3 Example regression results

The multiple regression results for global cropland at 2050 and 2100 are given in Tables C-4 and C-5, based on minimizing the AIC score. The scenario variables that meet a 5% significance threshold are population in the 2050 regression, and global trade and technology change in the 2100 regression. All three seem to have a coefficient that seems intuitively plausible, higher population is associated with higher cropland due to greater demand, greater global trade with lower cropland due to shifts in productions to areas where greatest yields can be achieved, and higher technology change with lower areas. At both dates a high degree of significance is seen for model type, however the model type identified as highly significant changes from hybrid in 2050 to CGE in 2100. In comparison to PE models, in all cases but hybrid at 2100 a lower area is suggested (negative coefficients), however the scale of the shift changes between the dates.

Number of cells is seen as highly significant in 2050, but less so by 2100, with the sign of the coefficient changing. It is not clear what the mechanisms is for such a high association between cropland and the model resolution. The coefficient for technology change also changes sign, at 2050 a higher technology change is associated with a higher cropland area, but this variable is given a low significance and hence has a low fraction of variance (~2%) in Figure 3-3.

Tables C-6 and C-7 show the regression results for European cropland at 2050 and 2100. The results for model type show CGE models are significantly lower than the PE models at both time points. The scenario variables indicated as significant at the 5% level are trade in the 2050 regression, and GDP growth rate, inequality, and population in the 2100 regression. The signs of the coefficients for these trade and population variables appears intuitively plausible, as in the global regressions discussed above. GDP growth rate and inequality are harder to have a clear perception as to direction of there likely impact on European cropland. The regression suggests that higher global GDP growth and higher global inequality are associated with lower cropland areas within Europe. However, no significant association is seen in the global regressions [Tables C-4 and C-5], potentially suggesting a shift of cropland from Europe to other regions under higher GDP growth rate or inequality.

Table C-4. Multiple linear regression output for global cropland at 2050, based on AIC selection criteria.

Variable	Estimate	Std. Error	t value	Pr (>|t)
(Intercept)	460.86	583.44	0.790	0.433829
Number of model cells (log)	99.33	23.10	4.300	9.34e-0.5***
Population at 2100	88.13	32.05	2.750	0.008615**
Technology change	149.50	107.26	1.394	0.170365
Model type: CGE	-242.68	135.84	-1.786	0.080910.
Model type: Hybrid	-499.04	138.11	-3.613	0000772***
Model type: Rule-based	-37.27	123.06	-0.303	0.763456

Significance codes: *** < 0.001; ** < 0.01; * < 0.05; . <0.10

Multiple R-squared: 0.4906, Adjusted R-squared: 0.4212

AIC score: 588.91

Table C-5. Multiple linear regression output for global cropland at 2100, based on AIC selection criteria.

Variable	Estimate	Std. Error	t value	Pr (>|t)
(Intercept)	3913.9619	652.1531	6.002	2.87e-06***
Scenario delta	2.7527	0.6974	3.947	0.000568***
Number model cells (log)	-202.449	42.693	-4.742	7.27e-05***
GDP growth rate to 2100	311.9289	171.0281	1.824	0.080153.
CO_2 concentration 2100	0.2473	0.1428	1.731	0.095716.
Population at 2100	-67.4064	36.9303	-1.825	0.079937.
Technology change	-405.9651	139.093	-2.919	0.007335**
Global trade	-288.3244	97.808	-2.948	0.006842**
Model type: CGE	-696.0373	142.2417	-4.893	4.91e-05***
Model type: Hybrid	12.273	170.538	0.072	0.943201
Model type: Rule-based	-404.9056	157.867	-2.565	0.016709*

Significance codes: *** < 0.001; ** < 0.01; * < 0.05; . <0.10

Multiple R-squared: 0.8048, Adjusted R-squared: 0.7267

AIC score: 394.65

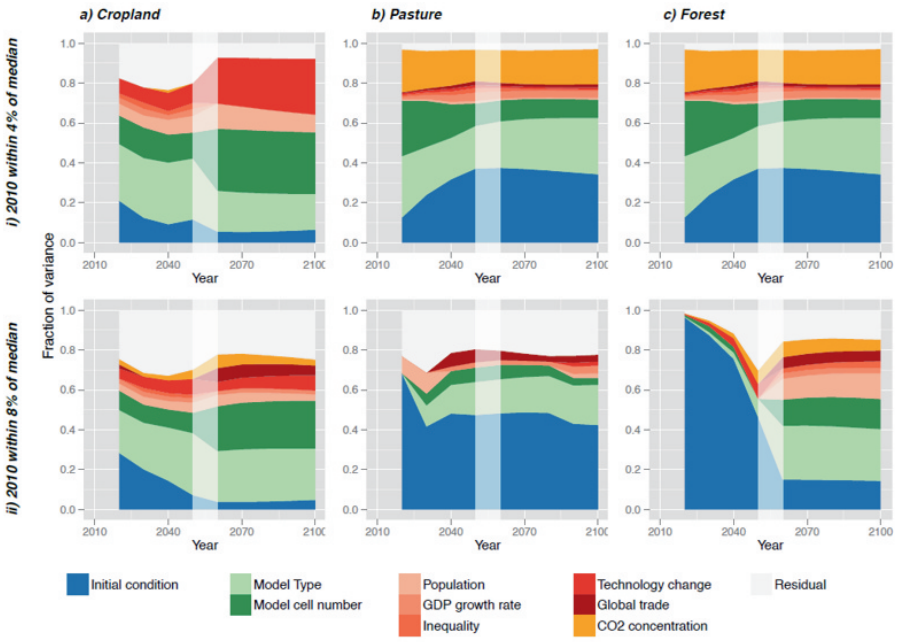

Figure C-9. Relative importance of different variance components restricted to scenarios that are within 4% (i), and 8% (ii) of the median area at 2010, for global land-cover areas. The number of scenarios included at 2020 with a 4% limit are 35, 18, and 13 and with a 8% limit are 41, 27, and 25 for cropland, pasture, and forest, respectively.

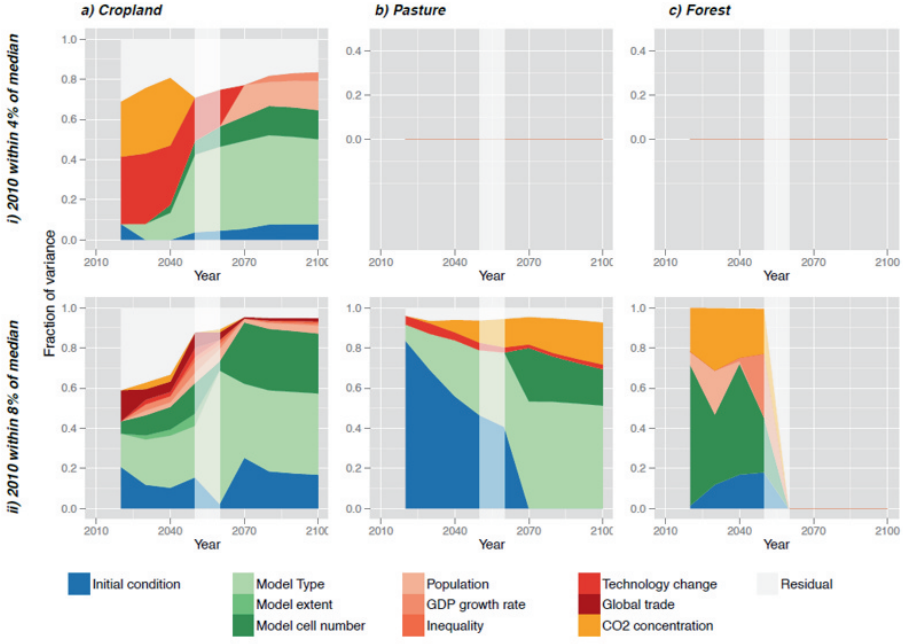

Figure C-10. Relative importance of different variance components restricted to scenarios that are within 4% (i) and 8% (ii) of the median area at 2010, for European (EU27) land-cover areas. The number of scenarios included at 2020 with a 4% limit are 20, 0, and 7, and with a 8% limit are 39, 14, and 9 for cropland, pasture, and forest, respectively. No data is plotted if the statistics cannot be calculated due to insufficient scenarios that meet the constraint.

Table C-6. Multiple linear regression output for European cropland at 2050, based on AIC selection criteria.

Variable	Estimate	Std. Error	t value	Pr (>|t)
(Intercept)	147.1846	9.5958	15.338	< 2e-16***
Scenario delta	0.6356	0.1863	3.411	0.001306**
Global trade	-9.4837	3.7336	-2.54	0.014304*
Model type: CGE	-33.0626	8.9759	-3.684	0.000574***
Model type: Hybrid	-3.9248	9.0715	-0.433	0.667163
Model type: Rule-based	-8.2172	7.4601	-1.101	0.276069

Significance codes: *** < 0.001; ** < 0.01; * < 0.05; . <0.10

Multiple R-squared: 0.4922, Adjusted R-squared: 0.4404

AIC score: 332.60

Table C-7. Multiple linear regression output for European cropland at 2100, based on AIC selection criteria.

Variable	Estimate	Std. Error	t value	Pr (>|t)
(Intercept)	3913.9619	652.1531	6.002	2.87e-06***
Scenario delta	2.7527	0.6974	3.947	0.000568***
Number model cells (log)	-202.449	42.693	-4.742	7.27e-05***
GDP growth rate to 2100	311.9289	171.0281	1.824	0.080153.
CO_2 concentration 2100	0.2473	0.1428	1.731	0.095716.
Population at 2100	-67.4064	36.9303	-1.825	0.079937.
Technology change	-405.9651	139.093	-2.919	0.007335**
Global trade	-288.3244	97.808	-2.948	0.006842**
Model type: CGE	-696.0373	142.2417	-4.893	4.91e-05***
Model type: Hybrid	12.273	170.538	0.072	0.943201
Model type: Rule-based	-404.9056	157.867	-2.565	0.016709*

Significance codes: *** < 0.001; ** < 0.01; * < 0.05; . <0.10

Multiple R-squared: 0.8048, Adjusted R-squared: 0.7267

AIC score: 394.65